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Anomalous transport properties of indium doped single crystals of bismuth

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Abstract : The transport properties of single crystal of bismuth doped with Indium have been investigated in the temperature range 100 to 300 K. The results of Hall coefficient and Thermo-electric-power show an anomalous behaviour doping with acceptor impurities making the substance n-type

Keywords : Galvanomagnetic and diamagnetic properties, indium doped single crystal of bismuth, anomalous behaviour

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The electronic properties of bismuth are due to the carriers in three bands - one conduction band (L_c) and two valence bands (L_v and T_v) . The valence band T_v overlaps with the conduction band L_c (See Figure 1). The overlap is small (~ 0.028 eV) and the energy gap

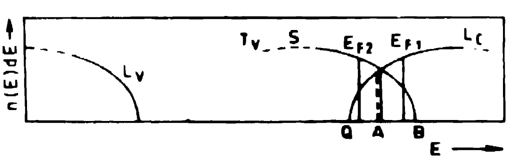

Figure 1. Projection of energy bands L_c and T_v on a two dimensional plane
E_{f1} : Fermi surface for Bi doped with donor.
E_{f2} : Fermi surface for Bi doped with acceptor.

between the conduction band and 2nd valence band is ~0.015 eV [1]. Due to the overlap, doping with donor or acceptor impurities induce interesting changes in properties exhibited by the sample. When acceptor impurity is added, electrons from both L_c and T_v bands go to the acceptor levels thus decreasing available free electrons in L_c and increasing free holes in T_v, so that $p > n$.

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Investigations with small percentages of impurities were carried out earlier and in our laboratory the same has been done with the higher percentages of impurities [2–9]. The aim of adding higher percentage of acceptor impurity is to deplete the number of electrons in L_c as much as possible and to increase the number of free holes in T_v. Since doping with higher percentages of Pb and Sn is not possible [8] we have doped Bi with In, whose power of accepting electrons is more than Pb or Sn. Therefore, it is expected that a smaller percentage of In would produce an effect larger than higher percentage of Sn of Pb. We have prepared single crystals of Bi in which we have added 1% In.

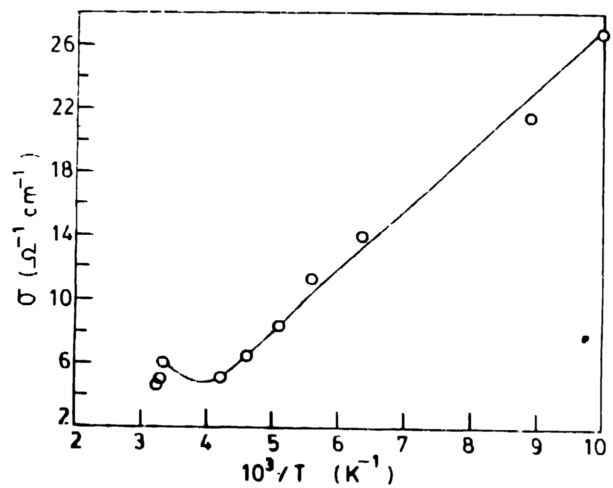

Figure 2. Plot of conductivity σ against $10^3/T$ for Bi + 1.0 at % In

We have observed the temperature variation of electrical conductivity, Hall effect, thermoelectric power, magnetoresistance and the diamagnetic susceptibility of the sample prepared (bismuth doped with 1% In). The results are shown in Figures 2 to 6. The temperature variation of Hall-coefficient and thermoelectric power are surprisingly different from those observed in other acceptor doped bismuth.

Here we present a comparison of the observations that have been made with the present sample and the previous samples to show the anomalies as clearly as possible.

In case of Pb and Sn-doped samples, the electrical conductivity (σ) initially decreases with rise of temperature linearly with $\frac{1}{T}$ and then increases [8,9]. As the doping percentage increases, the turning point moves to higher temperature. In the present case, also the variation of σ with temperature shows a similar variation and the turning point (260 K) seems to be higher than any of the samples observed before.

The Hall coefficient (R_H) of Pb or Sn-doped Bi shows positive values at low temperature. With rise of temperature, after an initial increase the positive value of R_H decreases. For smaller percentages of impurities, R_H becomes negative and for other samples, the intention to become negative lessens with increase of doping percentage [8,9]. But in the present case of In doped Bi, for the low value of magnetic field (~ 1 KG to 4.3 KG), R_H has

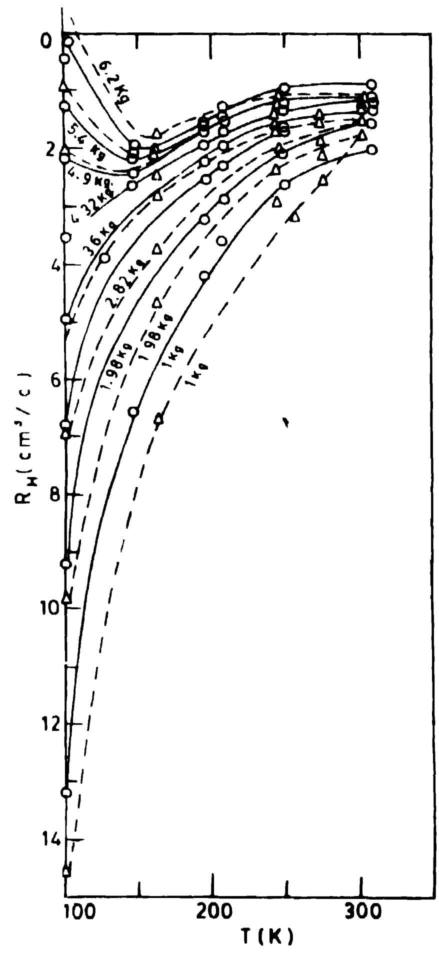

Figure 3. Plot of Hall coefficient R_H against T for Bi + 1.0 at % In, ○ sample No. 1; Δ-sample No. 2.

a large negative value at low temperature. With rise of temperature, the negative value of R_H decreases but remains negative throughout the range of temperature (100 K – 300 K). At higher magnetic field (~ 5.4 KG) the negative value of R_H becomes small or attains a small positive value which with rise of temperature shows an initial increase in the negative value and then again decreases but never becomes positive. The nature of the curve does not show any tendency to become positive at higher temperatures.

The thermoelectric power θ of Pb or Sn-doped Bi are positive at low temperatures. θ gradually decreases and becomes negative at higher temperature [9]. In the present case (Bi doped with In), it is negative at low temperature which initially increases and then the negative value decreases but does not become positive, rather the negative value shows a tendency to increase again.

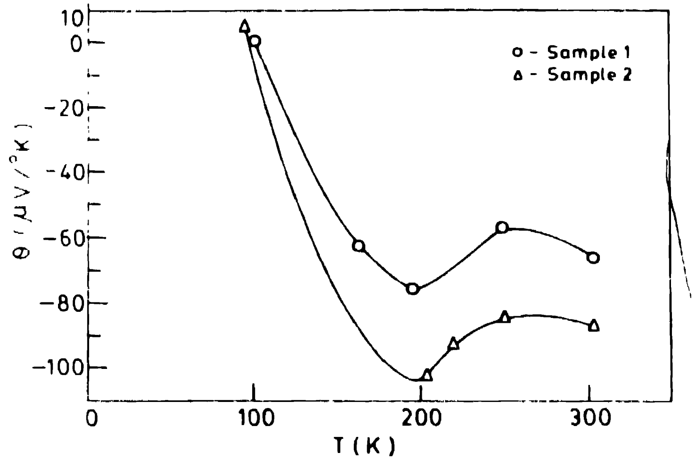

Figure 4. Plot of thermoelectric power θ against T for Bi + 1.0 at % In, O-sample No 1; Δ-sample No 2

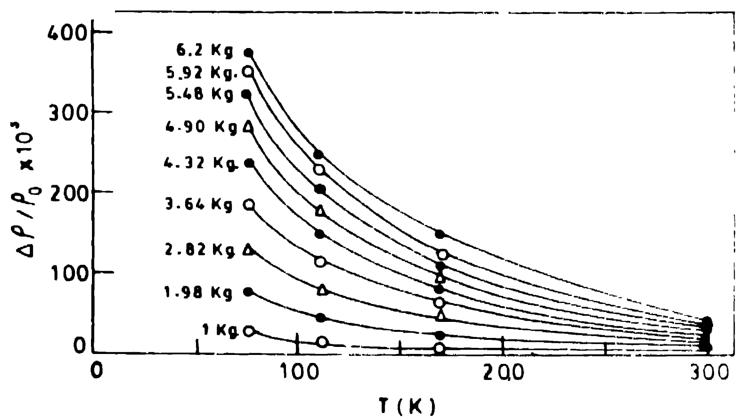

Figure 5. Plot of magnetoresistance $\frac{\Delta\rho}{\rho_0}$ against T for Bi + 1.0 at % In

The magnetoresistance $\frac{\Delta\rho}{\rho_0}$ shows a temperature dependence. In case of Pb and Sn-doped samples, the samples with lower percentage of impurity show maxima in the temperature variation of magneto-resistance. But in case of higher percentage of impurity (0.7% Sn), the sample does not show any maximum [9]. Here in In-doped sample also, there is no maximum and the value of $\frac{\Delta\rho}{\rho_0}$ is much larger than the former ones.

The temperature variation of magnetic susceptibility χ_{11} of Bi doped with In is also entirely different from the Pb and Sn-doped samples, though they all are diamagnetic in nature. The temperature variation of χ_{11} in Pb and Sn-doped samples, shows a maximum value with the exception of the sample with the highest percentage *i.e.* 0.7% of Sn dopings which does not show any maximum within the region of temperature studied. The value of

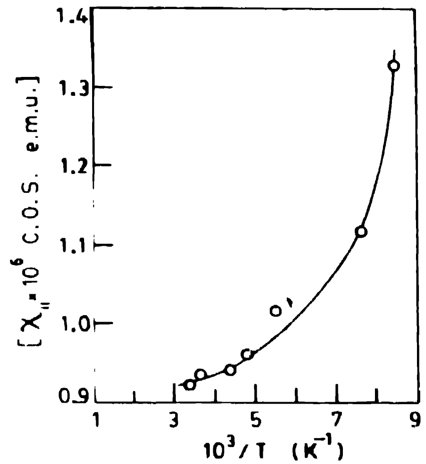

Figure 6. Plot of magnetic susceptibility χ_{11} against $1/T$ for Bi + 1.0 at % In

χ_{11} shows a decrease with increase of doping [10]. In the present case, the temperature variation of χ_{11} does not show any maximum but shows a decrease with rise of temperature but the values of χ_{11} is much larger than all the doped samples of Bi

Thus the present investigation shows that wherever the property depends on the nature of carrier, some unconventional behaviour is exhibited by the samples doped with indium. Doping with acceptors is making the sample n-type! From both Hall effect and thermoelectric power, it appears to be so. Further investigations are in progress.

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